NASA TECHNICAL MEMORANDUM

NASA TM X- 52369

NASA TM X- 52369

DETERMINATION OF REACTIVITIES USING PULSED NEUTRON TECHNIQUES FOR HIGHLY SUBCRITICAL SOLUTION REACTORS

by Daniel Fieno, Thomas A. Fox, Robert A. Mueller,
and C. Hubbard Ford
Lewis Research Center
Cleveland, Ohio

TECHNICAL PAPER proposed for presentation at
Winter Meeting of the American Nuclear Society
Chicago, Illinois, November 5-9, 1967

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION · WASHINGTON, D.C. · 1967

DETERMINATION OF REACTIVITIES USING PULSED NEUTRON TECHNIQUES FOR HIGHLY SUBCRITICAL SOLUTION REACTORS

by Daniel Fieno, Thomas A. Fox, Robert A. Mueller,
and C. Hubbard Ford

Lewis Research Center
Cleveland, Ohio

TECHNICAL PAPER proposed for presentation at

Winter Meeting
of the American Nuclear Society
Chicago, Illinois, November 5-9, 1967

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

DETERMINATION OF REACTIVITIES USING PULSED NEUTRON TECHNIQUES FOR HIGHLY SUBCRITICAL SOLUTION REACTORS

by Daniel Fieno, Thomas A. Fox,
Robert A. Mueller, and C. Hubbard Ford

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio

E-4054

INTRODUCTION

The NASA zero power solution reactors are convenient for performing pulsed neutron experiments and making corresponding calculations for systems ranging from critical to highly subcritical. These reactors consist of solutions of enriched (93.2 percent U^{235}) uranyl fluoride salt (UO_2F_2) dissolved in water and contained in a cylindrical aluminum vessel. For a given concentration of uranyl fluoride salt in water, criticality is achieved by adjusting the height of the solution. No control rods are associated with these solution reactors. The geometry is thus ideal for performing pulsed neutron experiments. The reactor used for the pulsed experiments reported herein is described by Fox, et al.[1]

The NASA solution reactor can thus be pulsed as a subcritical, homogeneous, unreflected thermal system. The reactor is made subcritical by simply lowering the solution height. Since the system is homogeneous and unreflected, the delayed component of each mode is expected to have the same energy and spatial distributions as the corresponding prompt component. Thus, several important theoretical limitations on the so-called "area" methods of Garelis and Russell,[2] Sjostrand,[3] and Gozani[4] for determining subcritical reactivities are removed.

Reactivities were determined using these "area" methods and compared to absolute criticality calculations for a large range of shutdown reactivities.

In addition, the method of Simmons and King[5] for determining subcritical reactivities from the measured prompt fundamental mode decay constants of a subcritical and corresponding delayed critical system was applied.

EXPERIMENTAL GEOMETRY

Figure 1 is a schematic drawn to scale of the solution reactor used for the pulsed neutron experiments. Although there is provision for a water side reflector, the experiments were performed with the system unreflected. The inside diameter of the cylindrical tank is 76.2 centimeters. For a fuel solution having a hydrogen to uranium-235 atom ratio of 975 the nominal solution height at delayed critical is 26.8 centimeters. The resulting reactor is disk shaped with a height to diameter ratio of 0.35. The cylindrical reactor vessel is made of aluminum having a side wall thickness of 0.70 centimeters and a bottom plate thickness of 1.27 centimeters.

The pulsed neutron source was centered at the bottom of the reactor tank. The neutron detector was a BF_3 (96 percent B^{10}) proportional counter. The measurements were made with this detector located in the fuel solution. The detector was positioned at 0.44 of the tank radius and at two-thirds of the solution height. The BF_3 detector in this system acts as a point detector (0.8 centimeter diameter) and does not appreciably perturb the measurements.

EXPERIMENTAL PROCEDURE

For a given subcritical solution height, the reactor was pulsed repetitively until adequate counting statistics were obtained. Figure 2 is a block diagram of the electronic equipment arrangement used for these ex-

periments. The subcritical reactor was pulsed at a rate of 5 to 6 pulses per second. The multichannel analyzer had a channel width of 400 microseconds for subcritical systems near delayed critical while the width for the highly subcritical systems was 50 microseconds. For systems near delayed critical the data were collected over an interval of about 5 minutes while for the highly shutdown systems about 90 minutes were required to obtain a sufficient number of counts.

Figure 3 is a schematic representation of an idealized pulsed neutron experiment. The background corrected logarithm of the detector response is plotted as a function of the analyzer channel number. Shown is the equilibrium delayed neutron contribution persisting following the decay of the prompt neutron portion of the curve. The slope of the prompt portion of the curve yields the prompt fundamental mode decay constant. The areas corresponding to the time integrals of the prompt as well as the delayed neutrons are also shown on the figure.

Figure 4 indicates how the experimental data obtained for a subcritical reactor are related to the reactivities evaluated by the various "area" methods mentioned previously. The reactivity in dollars for the "area" method of Sjostrand is obtained by taking the ratio of the prompt neutron area to the delayed neutron area. The reactivity in dollars for the "area" method of Gozani is obtained by taking the ratio of the extrapolated prompt fundamental mode area to the delayed neutron area. In the Garelis-Russell method, the prompt neutron response is weighted by the factor exp (ct), then integrated over time. The quantity c is adjusted so that this integral equals the prompt plus delayed neutron area. The reactivity in dollars

is then given by

$$\rho(\$) = \frac{\alpha_o}{c} + 1$$

where α_o is a negative number, the prompt fundamental mode decay constant. For the Simmons-King method the reactivity in dollars is given by

$$-\rho(\$) = \frac{\alpha_o - \alpha_c}{\alpha_c}$$

where α_c is the prompt fundamental mode decay constant measured at delayed critical.

The experimental data were reduced using a modified version of a computer program developed by Masters.[6] This program also computes experimental errors based on counting statistics only.

ABSOLUTE CRITICALITY CALCULATIONS

One dimensional calculations along the axis of these cylindrical systems were performed using the Sn method. The aluminum bottom plate was explicity considered in the transport calculations. The S_4 approximation with the elastic scattering treated in P_1 approximation was found to be adequate in treating the neutron leakage from the ends of these subcritical solution reactors. Radial leakage was calculated from the radial buckling of the system. These calculations used eight energy groups - seven fast and one thermal group which included an up-scattering transfer component. The fast group cross sections were obtained using the GAM-II code[7] while the thermal group cross sections were obtained using the GATHER-II code[8]. Calculations using this Sn method along with GAM-GATHER cross sections have accurately predicted the criticality of these solution reactors over a wide

range of composition and configuration.[9] For these experiments the delayed critical height was calculated to be 26.80 centimeters for the fuel solution having a hydrogen to uranium-235 atom ratio of 975. This calculated value differs from the corresponding experimental value by less than 0.20 centimeters.

The prompt fundamental mode decay constants and subcritical reactivities for various solution heights were calculated from the Sn results by a procedure described by Wallace, et al.[10] Excellent discussions of the calculation of the prompt fundamental mode decay constant and corresponding value of the subcritical reactivity are also given by Masters, et al.[11] and by Preskett, et al.[12]

RESULTS

Using the methods discussed, calculations and experiments have been performed for a range of fuel solution heights. The calculated variation with solution height of the reactor parameters required are presented in figures 5-8. Calculated values of the effective multiplication factor, K_{eff}, are shown in figure 5. The K_{eff} varies from about 0.64 to 1.00 for a fuel solution height varying from about 13 to 26.8 centimeters. Figure 6 shows the prompt neutron lifetime as a function of fuel solution height. Over the range of fuel solution heights studied, the lifetime varies from about 59 to 64 microseconds. Figure 7 shows the variation of the effective delayed neutron fraction, β_{eff} with solution height. β_{eff} varies from 0.00520 to 0.00736 over the range of fuel solution heights studied. The value of β was taken as 0.0065 for uranium-235. Figure 8 shows the variation of the parameter β_{eff}/l as a function of fuel solution height. This

parameter varies from about 89 to 115 per second over the range of fuel solution heights studied.

Figure 9 shows the calculated and experimental value of the prompt fundamental mode decay constant, α_o, in sec^{-1} as a function of difference of solution height from delayed critical, ΔH, in centimeters. At delayed critical the value of α_o is about 115. Calculated values of α_o from 115 to about 2500 agree well with experimental values. This corresponds to ΔH varying from 0 to 7.5 centimeters. For values of ΔH from 7.5 to over 12 centimeters, the calculated values are somewhat higher than the corresponding experimental values. For the extreme values of ΔH the calculated values of α_o are about 10 percent higher than the experimental values. Table 1 shows the same data in tabulated form.

Figure 10 shows the calculated and experimental value of the reactivity, ρ, in dollars as a function of solution height from delayed critical. The reactivity varied from zero to about 50 dollars. As can be seen the "area" method of Sjostrand for determining reactivity agrees reasonably well with the calculated values over the range considered. The "area" methods of Garelis-Russell and Gozani for determining reactivity gave nearly the same values over the range considered. Both the Garelis-Russell and Gozani "area" methods gave higher values for the reactivity by from 10 to 20 percent than did either the method of Sjostrand or the theoretical calculations.

Table 2 presents the reactivity determinations in tabular form. Also shown are values of the reactivity calculated by the method of Simmons and King. Beyond a few dollars of reactivity, this method gave values considerably lower than the calculated values.

CONCLUSIONS

A number of conclusions result from this study of an unreflected, homogeneous, thermal solution reactor from criticality to about \$50 shutdown:

1. Calculated values of the prompt fundamental mode decay constants agree well with experimentally determined values.

2. The "area" method of Sjostrand for determining reactivity agrees reasonably well with the calculated values over the entire range.

3. The "area" methods of Garelis-Russell and Gozani both predicted reactivities that are consistently higher by 10 to 20 percent than the calculated values and were in agreement with each other.

4. All of the area methods are sensitive to an accurate experimental determination of the equilibrium delayed neutron background.

5. The method of Simmons and King gave values for the reactivity considerably lower than the calculated values over most of the range of solution heights considered. The method fails because the value of β/l used is that at delayed critical which changes strongly with increasing subcriticality.

REFERENCES

1. T. A. Fox, R. A. Mueller, C. H. Ford, and D. L. Alger, "Critical Mass Studies with NASA Zero Power Reactor II. I. Clean Homogeneous Configurations," NASA TN D-3097 (Nov. 1965).

2. E. Garelis and J. L. Russell, Jr., "Theory of Pulsed Neutron Source Measurements," Nucl. Sci. Eng., 16, 263 (1963).

3. N. G. Sjostrand, "Measurements on a Subcritical Reactor Using a Pulsed Neutron Source," Arkiv Fysik, 11, 233 (1956).

4. T. Gozani, "A Modified Procedure for the Evaluation of Pulsed Source Experiments in Subcritical Reactors," Nukleonik, 4, 348 (1962).

5. B. Simmons and J. S. King, "A Pulsed Neutron Technique for Reactivity Determination," Nucl. Sci. Eng., 3, 595 (1958).

6. C. F. Masters, "A Procedure for Evaluating Modified Pulsed Source Experiments in Subcritical Nuclear Reactors," CURL 16, Cornell University (Sept. 1966).

7. G. D. Joanou and J. S. Dudek, "Gam-II. A B_3 Code for the Calculation of Fast-Neutron Spectra and Associated Multigroup Constants," GA-4265, General Atomic (Sept. 16, 1963).

8. G. D. Joanou, C. V. Smith, and H. A. Vieweg," GATHER-II. An IBM-7090 Fortran-II Program for the Computation of Thermal-Neutron Spectra and Associated Multigroup Cross Sections," GA-4132, General Atomic (July 8, 1963).

9. D. Fieno, "Transport Study of the Real and Adjoint Flux for NASA Zero Power Reactor (ZPR-1)," NASA TN D-3990 (May 1967).

10. S. K. Wallace, K. R. Teare, and J. B. Green, "Methods for the Comparison of Pulsed Neutron Shutdown Measurements with Theory," Nucl. Sci. Eng., 25, 407 (1966).

11. C. F. Masters and K. B. Cady, "A Procedure for Evaluating Modified Pulsed-Neutron Source Experiments in Subcritical Nuclear Reactors," Nucl. Sci. Eng., 29, 272 (1967).

12. C. A. Preskitt, E. W. Nephew, J. R. Brown, and K. R. Van Howe, "Interpretation of Pulsed-Source Experiments in the Peach Bottom HTGR," Nucl. Sci. Eng., 29, 283 (1967).

E-4054

PROMPT FUNDAMENTAL MODE DECAY CONSTANTS FOR NASA SOLUTION REACTOR

SOLUTION HEIGHT FROM CRITICALITY, $-\Delta H$ (CM)	PROMPT FUNDAMENTAL MODE DECAY CONSTANT, α_0 (SEC^{-1})	
	CALCULATED	EXPERIMENTAL*
0	116	128 ± 0.6
0.13	145	156 ± 0.5
0.26	174	181 ± 0.5
0.51	225	234 ± 0.5
0.76	280	289 ± 0.5
1.03	340	348 ± 0.6
2.01	590	572 ± 1.2
3.06	870	840 ± 2.3
4.04	1170	1110 ± 2.4
5.08	1520	1434 ± 3.3
6.12	1890	1791 ± 3.4
7.10	2275	2159 ± 5.2
8.14	2740	2548 ± 5.8
9.15	3240	3008 ± 6.2
10.65	4070	3795 ± 11
12.17	5100	4626 ± 14

*INDICATED ERRORS ARE STANDARD DEVIATIONS BASED ON COUNTING STATISTICS ONLY.

CS-44795

TABLE I

REACTIVITIES FOR NASA SOLUTION REACTOR

SOLUTION HEIGHT FROM CRITICALITY, $-\Delta H$ (CM)	REACTIVITY, -P ($)*				
	CALC.	SJOSTRAND	GOZANI	GARELIS-RUSSELL	SIMMONS-KING**
0.13	0.26	0.23 ± 0.002	0.24 ± 0.001	***	0.34
0.26	0.52	0.49 ± 0.003	0.51 ± 0.002	0.35 ± 0.004	0.56
0.51	1.04	1.08 ± 0.01	1.12 ± 0.01	0.99 ± 0.01	1.02
0.76	1.53	1.71 ± 0.01	1.80 ± 0.01	1.76 ± 0.01	1.49
1.03	2.07	2.29 ± 0.01	2.41 ± 0.01	2.40 ± 0.02	2.00
2.01	4.30	4.78 ± 0.05	5.12 ± 0.05	5.08 ± 0.07	3.93
3.06	6.93	7.50 ± 0.10	8.22 ± 0.10	8.13 ± 0.17	6.24
4.04	9.60	9.94 ± 0.12	11.08 ± 0.13	10.95 ± 0.27	8.57
5.08	13.00	12.79 ± 0.17	14.66 ± 0.19	14.48 ± 0.43	11.36
6.12	16.80	16.36 ± 0.20	19.24 ± 0.23	19.06 ± 0.60	14.44
7.10	20.60	20.36 ± 0.32	24.09 ± 0.38	23.82 ± 1.1	17.61
8.14	25.50	25.32 ± 0.44	30.15 ± 0.52	29.43 ± 1.7	20.97
9.15	30.90	30.36 ± 0.68	35.82 ± 0.80	35.32 ± 2.1	24.93
10.65	40.70	38.65 ± 1.2	45.57 ± 1.4	43.99 ± 3.8	31.72
12.17	53.40	47.45 ± 1.6	52.98 ± 1.8	53.96 ± 6.1	38.88

*EXPERIMENTAL ERRORS ARE STANDARD DEVIATIONS BASED ON COUNTING STATISTICS ONLY.

**BASED ON CALCULATED α_c OF 116.

***NOT OBTAINABLE FROM DATA.

CS-44799

TABLE II

E-4054

TYPICAL PULSING GEOMETRY FOR UNREFLECTED
NASA SOLUTION REACTOR

DRAWN TO SCALE

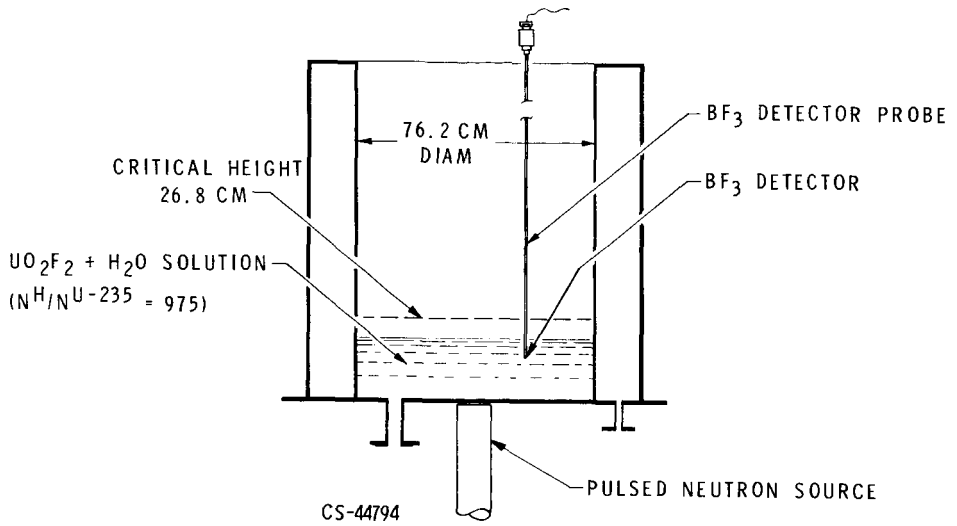


Figure 1.

DIAGRAM OF PULSED NEUTRON EXPERIMENTS
IN NASA SOLUTION REACTOR

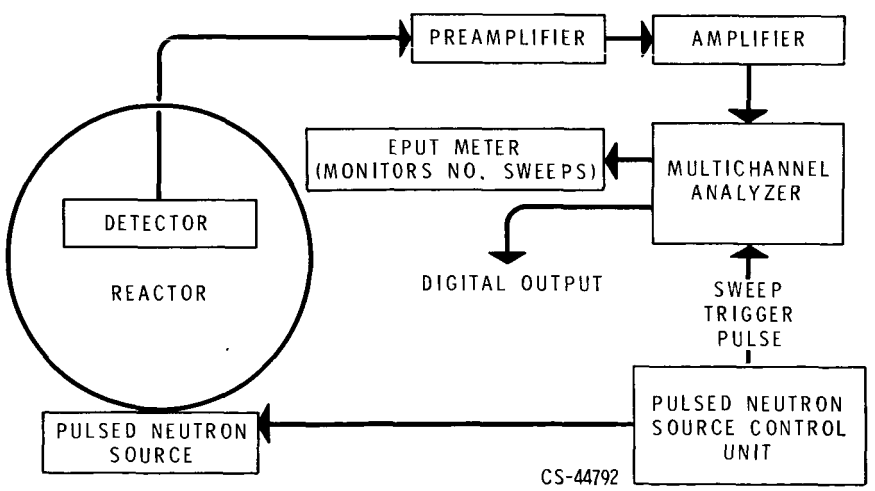


Figure 2.

IDEAL DETECTOR RESPONSE TO PULSED NEUTRON SOURCE

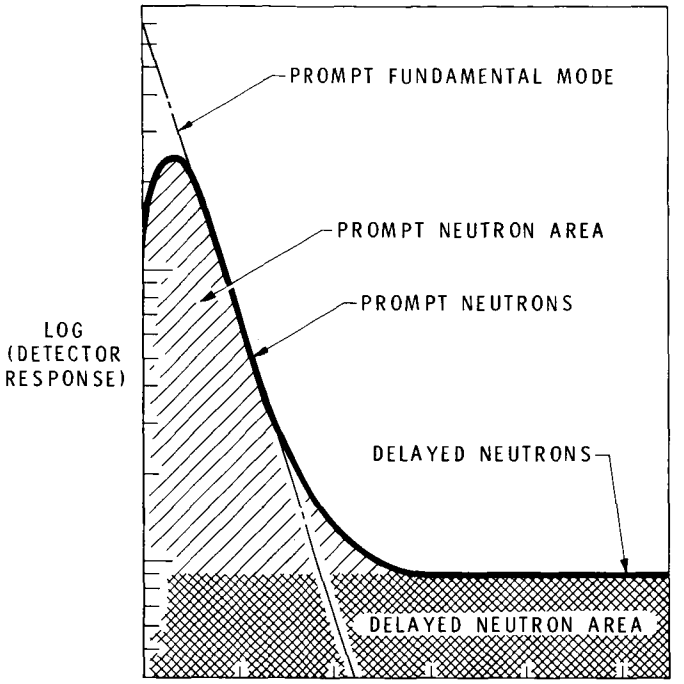


Figure 3.

DETERMINATION OF REACTIVITIES FROM EXPERIMENTAL DATA

A. MODIFIED PULSED NEUTRON EXPERIMENTS

1. SJÖSTRAND

$$-\rho(\$) = \frac{\text{PROMPT NEUTRON AREA}}{\text{DELAYED NEUTRON AREA}}$$

2. GOZANI

$$-\rho(\$) = \frac{\text{EXTRAPOLATED PROMPT FUNDAMENTAL MODE AREA}}{\text{DELAYED NEUTRON AREA}}$$

3. GARELIS-RUSSELL

$$\rho(\$) = \frac{\alpha_0}{c} + 1$$

WHERE c SATISFIES

$$\int_0^T Np(t)e^{ct}\,dt = \int_0^T Np(t)\,dt + \int_0^T Nd(t)\,dt$$

B. PULSED NEUTRON EXPERIMENTS

1. SIMMONS-KING

$$-\rho(\$) = \frac{\alpha - \alpha_c}{\alpha_c}$$

CS-44793

Figure 4.

EFFECTIVE MULTIPLICATION FACTOR VS. REACTOR HEIGHT

$N^{H}/N^{U-235} = 975$

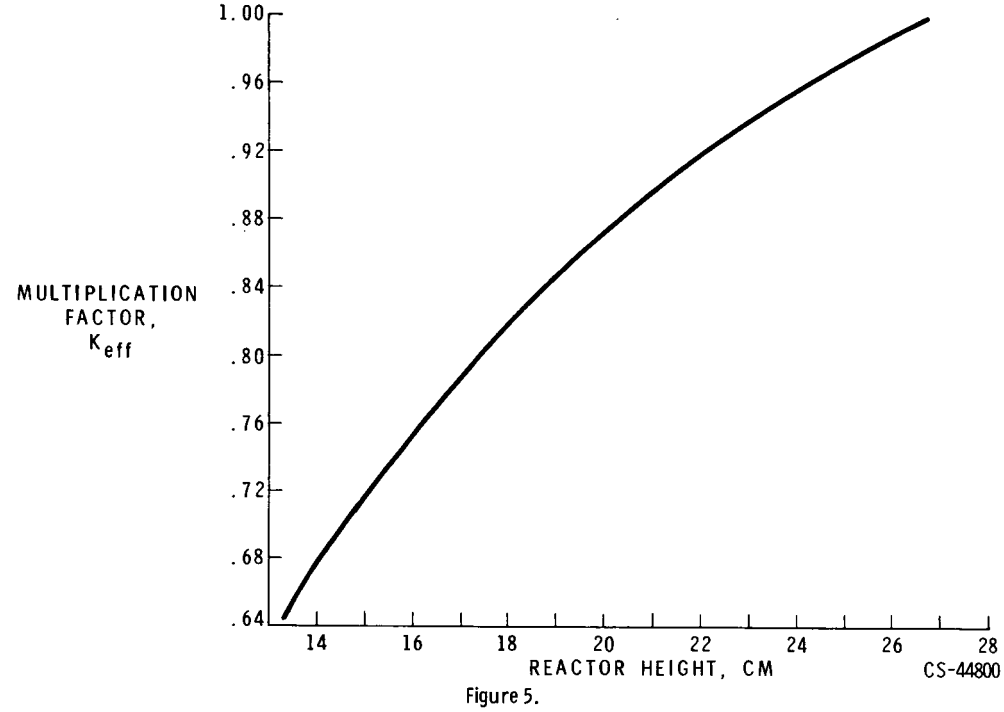


Figure 5.

NEUTRON LIFETIME VS. REACTOR HEIGHT

$N^{H}/N^{U-235} = 975$

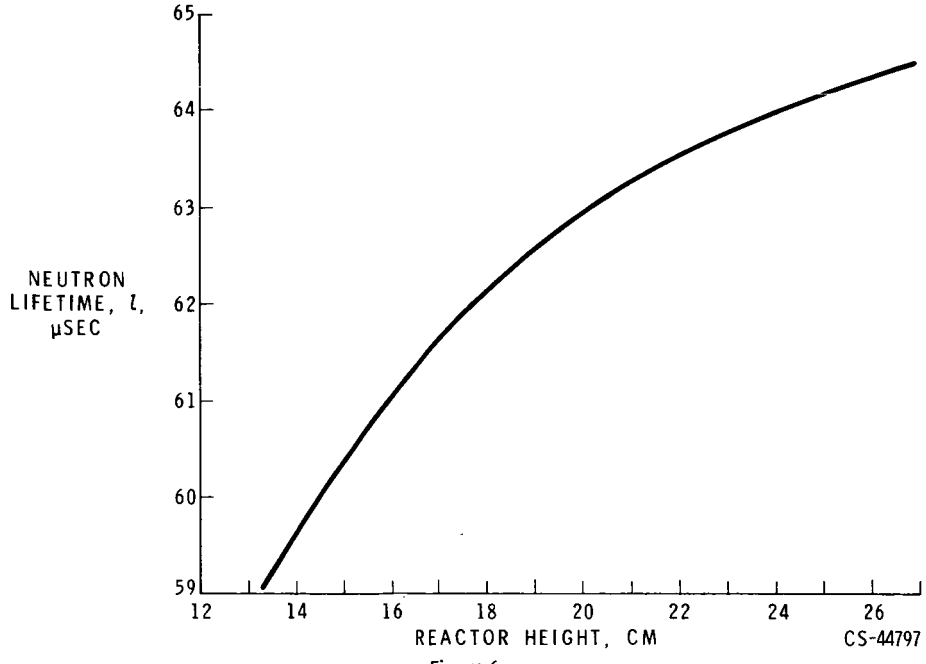


Figure 6.

EFFECTIVE DELAYED NEUTRON FRACTION VS. REACTOR HEIGHT

$N^H/N^{U-235} = 975$

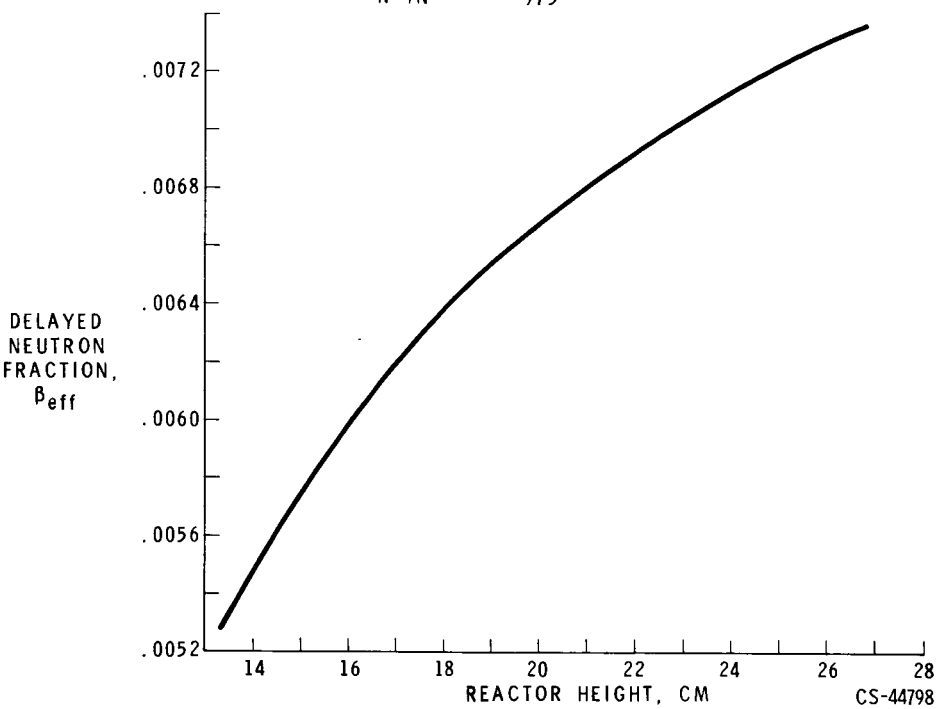


Figure 7.

β_{eff}/l VS. REACTOR HEIGHT

$N^H/N^{U-235} = 975$

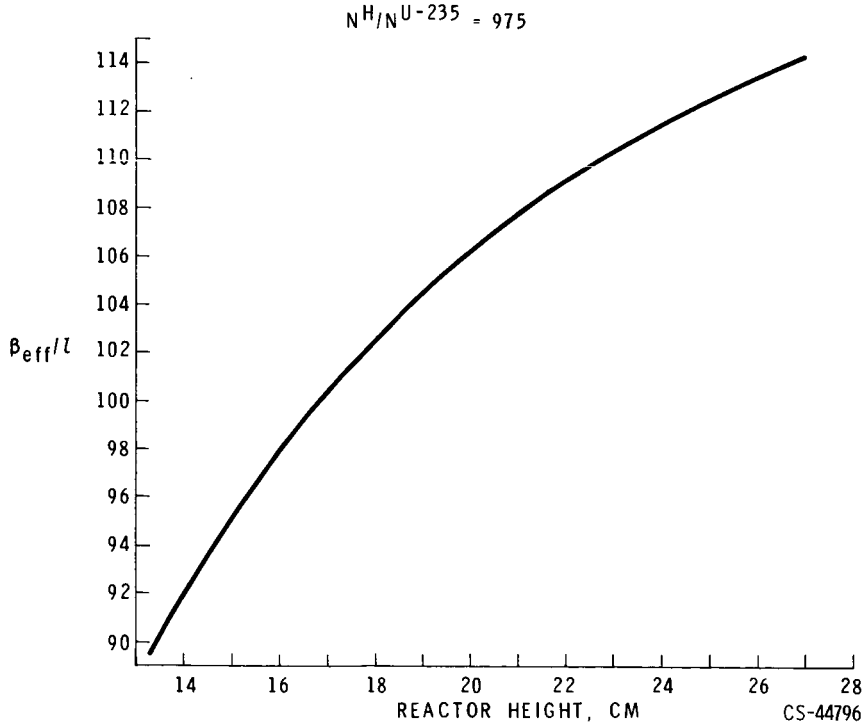
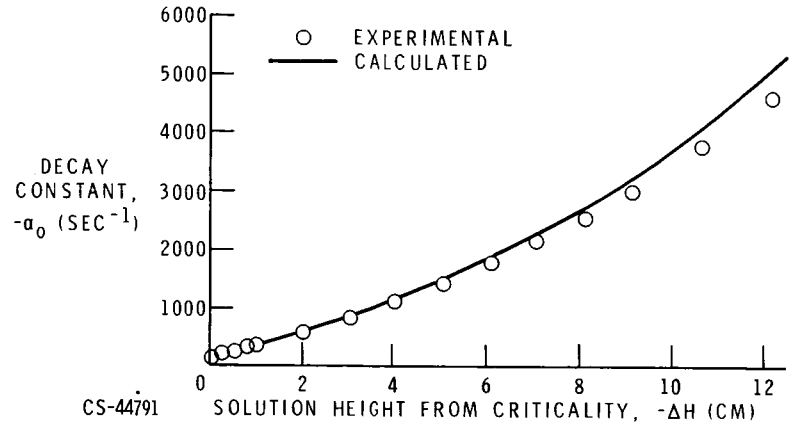


Figure 8.

DECAY CONSTANTS FOR NASA SOLUTION REACTOR

$N^{H}/N^{U-235} = 975$

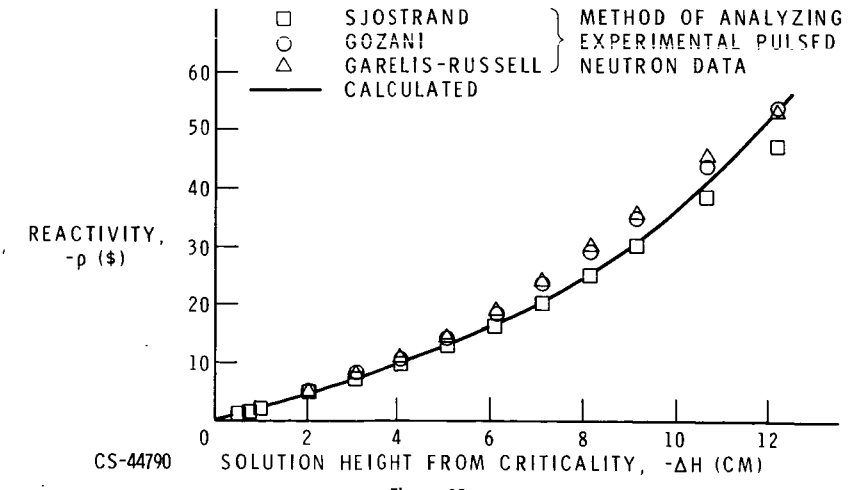


CS-44791

Figure 9.

REACTIVITIES FOR NASA SOLUTION REACTOR

$N^{H}/N^{U-235} = 975$



CS-44790

Figure 10.